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Integrated life-cycle optimisation and supply-side management for building retrofitting

Xiaojun Luo, Lukumon O. Oyedele *

Big Data Enterprise and Artificial Intelligence Laboratory (Big-DEAL), University of the West of England (UWE), Frenchay Campus, Bristol, BS16 1HH, United Kingdom

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ABSTRACT

Building retrofitting is a powerful approach to enhance building energy performance. The net-zero ambition urges the need to renovate building energy system in view of the life-cycle optimal, to address climate and environmental challenges. Existing retrofitting and optimisation solutions are generally based upon minimising operational energy or cost. However, although building retrofitting can reduce the energy use at the operating phase, additional materials would result in increased embodied energy. The objective of this paper is to devise a novel building retrofitting approach through the integration of life-cycle optimisation and supply-side management. It is an interactive two-set optimisation approach aimed at minimising overall life-cycle energy consumption through determining the optimal design configuration and operating plan of retrofitting energy devices. The essential retrofitting energy devices include passive retrofitting options (i.e., photovoltaic panel and solar thermal collector) and active retrofitting options (i.e., biomass boiler, ground source heat pump, heat storage, electricity storage, and cogeneration system). A modern 3-floor office building in Manchester, the United Kingdom, is adopted to assess the performance of the proposed refurbishment approach. The real-world situation is represented by historical electricity and gas consumption profiles, current building design information, historical weather profile, as well as life-cycle inventory information. The proposed retrofitting optimisation approach can help decision-makers select the optimal retrofitting solution so as to reduce the overall life-cycle energy consumption of office buildings.

1. Background

Greenhouse gas emissions from electricity and commercial heat used in buildings rose to 10 $GtCO_2$ worldwide in 2019, which is equivalent to 28% of total global energy-related carbon emissions [1]. Although new buildings are constructed with higher energy efficiency, considerable energy waste is generated by existing buildings [2]. Therefore, retrofitting measures taken on existing buildings will substantially contribute to the overall energy consumption reduction.

1.1. Literature review

Most of the state-of-the-art studies focused on using passive retrofitting measures to decrease operating energy consumption. For example, Asadi et al. [3] proposed a multi-objective optimisation model to choose the appropriate intervention measures aimed at minimising the energy usage in the building in a cost-effective manner. Four types of decision variables were considered in the optimisation process, including window type, external wall insulation materials, roof insulation materials and solar collector type. Fan et al. [4] proposed a multi-objective optimisation model for building envelope retrofitting. The decision variables included the type of windows, wall and roof insulation materials, and solar panels. The aim of the proposed retrofitting optimisation strategy was to increase operating energy consumption reduction capability, as well as decrease net present value and payback time. Chang et al. [5] proposed a multi-objective optimisation approach for selecting the optimal combination of building envelopes. Different types of alternative envelope options were selected for south, north, east, west walls and roof, respectively. The optimisation objectives included operating energy performance, indoor thermal comfort, environmental impacts and economic effects. Rosso et al. [6] managed to select the optimal combination of insulation materials using a genetic

Abbreviations: ACO, Ant colony optimisation; CHP, Combined heat and power; GA, Genetic algorithm; GSHP, Ground source heat pump; HVAC, Heating; ventilation and air conditioning. PV, Photovoltaic.

* Corresponding author.
E-mail addresses: Xiaojun.Luo@uwe.ac.uk (X. Luo), L.Oyedele@uwe.ac.uk, Ayolook2001@yahoo.co.uk (L.O. Oyedele).

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algorithm-based multi-objective optimisation algorithm. The main optimisation objective included minimising initial asset cost, operating energy cost, and greenhouse gas emissions. The decision variables included types of glazing system, opaque vertical and horizontal envelope insulation system, opaque envelope finishing layer optics characteristics, solar shading, sun space, solar thermal collector and PV panels. Alkhateeb et al. [7] assessed the potential of a holistic retrofitting approach in transforming a federal office building into a net-zero operating electricity consumption. The optimal integration of different grid-connected photovoltaic (PV) systems was investigated. In these studies, the energy-saving performance of these intervention measures purely depends on the weather condition, while no supply-side management strategy was needed.

Meanwhile, the performance of active retrofitting measures was also investigated. Through a differential evolution algorithm-based multi-objective optimisation model, Bo et al. [8] managed to maximise energy savings during a time period while minimising discounted payback period and the initial cost of the retrofitted building. The retrofitting focused on energy demand reduction through energy-efficient lighting, geyser and air conditioning systems. Jeong et al. [9] proposed a multi-objective optimisation approach to maximise carbon emission reduction for a multi-family housing complex during its operating stage. The retrofitting focused on the demand side, including types of envelope insulation materials, lighting systems, window systems, and shading systems. The multiple retrofitting objectives included savings-to-investment cost, net present value, initial investment cost, and marginal abatement cost. Felius et al. [10] conducted a simulation-based optimisation to investigate the cost-effective retrofitting combinations of building envelope, energy system and building automation control strategies. The automation control included heating, ventilation, lighting and solar shading control at different levels. The single optimisation objective was year-round energy consumption, while the life-cycle cost and thermal comfort of the optimal retrofitting combination was also assessed. In these studies, although lighting, heating and ventilation systems were adopted as retrofitting options, the constant load and efficiency was assumed, which was unable to reflect the real operating situation.

Recently, more attention has been paid to minimise life-cycle costs of the retrofitted building during its entire service life. Based on available investments, Jafari et al. [11] proposed a decision-making framework to select the optimal retrofitting options to maximise the homeowner economic benefits during the service life of the building. The various retrofitting options included the installation of envelope insulation, programmable thermostat, evaporative cooler, solar thermal collector, solar PV panel and ground source heat pump (GSHP), tuning up HVAC, as well as replacement of lights, refrigerator and dishwasher. Rabani et al. [12] proposed an optimisation approach to minimise life-cycle costs of the office building, while the retrofitting measures included types of window, external wall, ground floor, roof, external shading, ventilation airflow rate, and supply air temperature at the design stage. Shen et al. [13] evaluated the performance of a multi-objective approach in minimising the life-cycle cost of building retrofitting plan. The retrofitting options included U-value and solar heat gain coefficient of the transparent part of the building envelope, wall and roof insulation, natural ventilation and air infiltration value. Antipova et al. [14] proposed a rigorous mixed-integer linear program optimisation algorithm to minimise the life-cycle cost of retrofitting measures for a semi-detached house. The retrofitting options included different insulation materials, windows and solar panels. Al-Saadi et al. [15] presented a genetic algorithm (GA)-based optimisation approach for the envelope insulation design to minimise total life-cycle cost. The retrofitting measures included envelope insulation, thermal mass, airtightness, area of the window, type of glazing and window shading. Mejjaouli et al. [16] developed a decision-support model for selecting the optimal energy retrofitting strategies and minimising life-cycle cost. The energy retrofitting strategies included the replacement of air conditioners, lighting systems, refrigerators and other household appliances. These studies mainly focused on life-cycle economic impacts, while embodied energy and carbon of retrofitting materials. Moreover, the energy-saving performance of insulation materials, glazing systems, window shading, solar conversion systems mainly passively depends on weather conditions. For those replacements of lighting and air conditioning systems, it was assumed that the active energy system constantly worked at design capacity.

Although some scholars considered life-cycle energy and environmental performance, they mainly conducted the evaluation of life-cycle primary energy consumption and greenhouse gas emissions of different retrofitting measures. For instance, Gangolells et al. [17] devised a model to identify the life-cycle energetic, economic and environmental impacts of a set of energy renovation measures. The primary and secondary retrofitting measures were identified for each type of office building. It was found that the most efficient energy renovation measures included heat pump replacement and replacement of lamps with LEDs. Prabatha et al. [18] conducted a performance evaluation on both carbon emission and life-cycle cost with the implementation of different retrofitting measures, including envelope tightness, windows, wall, roof, space heating and hot water system, lighting system, water outlets and renewable integration. Rocchi et al. [19] developed a hybrid method for traditional rural building retrofitting design. The hybrid method was based upon integrating energy and comfort optimisation, life-cycle assessment and life-cycle costing analysis. Different envelope insulation materials are investigated, while polystyrene, kenaf, hemp and cellulose are found to be the most favourable materials. Shadram et al. [20] evaluated the performance of a multi-objective optimisation approach in selecting the optimal solutions for retrofitting towards minimum operating energy consumption and embodied energy. The investigated retrofitting solutions include adopting additional insulation on walls and roofs, replacement of existing windows with more energy-efficient ones, and replacing traditional mechanical extract ventilation with heat recovery ventilation. Martinopoulos et al. [21] investigated the life-cycle carbon emission performance of various solar conversion systems. It is demonstrated that the environmental impacts of solar energy conversion systems are considerably less than those of conventional energy sources. Piccardo et al. [22] investigated the life-cycle primary energy implications of different envelope insulation materials. The retrofitting options included thermal insulation, building claddings and energy-efficient windows. It was found that an appropriate selection of building materials could reduce the embodied energy by up to 40%. Shirazi et al. [23] investigated the potential retrofitting measurements to improve the operational energy consumption of the building scenarios and assessed its associated embodied impacts. The investigated retrofitting measures included various envelope insulation materials and replacement of HVAC system with a higher energy-efficient one. The main findings of this research showed that the highest environmental impacts were associated with the attic/knee insulation and HVAC unit's replacement through retrofitting residential buildings. Leo et al. [24] investigated the embodied energy and carbon of different retrofitting measures on 3 types of hotel buildings. The investigated retrofitting measures included draught sealing, blinds, ceiling and wall insulation, and a glazing system. Luo et al. [25] evaluated the life-cycle environment, economy and energy performance of passive retrofitting measures on an office building. The passive retrofitting measures included improving envelope thermal properties (e.g., wall insulation, roof insulation and triple-glazed windows) and installing renewable energy devices (e.g., PV panel, solar heater and wind turbine). Luo et al. [26] also proposed a life-cycle optimisation approach to maximise lifetime cost-saving, energy reduction and carbon reduction. The retrofitting options included roof insulation, wall insulation, wind turbine, solar heater, biomass boiler, CHP system and PV panel. However, in that study, biomass boiler and CHP system were operated at constant load, while no supply-side management strategy was adopted.

1.2. Research gaps

The literature mentioned above suggests that building retrofitting strategies can effectively reduce overall operational cost, energy consumption and carbon emission. Although various optimisation approaches have been proposed to select retrofitting solutions to achieve multiple economic, environmental and energetic objectives, the three significant research gaps are identified as follows:

- Lack of investigation on the integrated energy system

The effects of passive retrofitting measures (i.e., changing window type and glazing system [3,4,6,9,14,15], installing envelope insulation [3–6,9–15,25,26], and installing solar energy conversion system [3,4,7, 11,14,25,26]) have been widely investigated, while the active retrofitting measures, such as replacement of energy-efficient lighting and HVAC system [8–12,16] were also mentioned. However, there were few studies considering the integrated design of the comprehensive energy system. The well-designed integrated energy system, consisting of the combined installation of PV panels, solar thermal collectors, heat storage, electricity storage, biomass boiler, GSHP or combined cooling heat and power (CCHP) system, can cooperate in supplying heating and electrical energy at higher overall energy efficiency.

- Lack of supply-side management of retrofitting energy devices

For passive retrofitting options, such as envelope insulation, PV panel and solar thermal collector, the year-round thermal energy demand reduction and renewable energy production depend on actual weather data. Although the HVAC system replacement was considered in some of the previous works, its operating capacity was assumed constant all year-round. There is no study that investigates the supply-side management of retrofitting energy devices for reducing total operational energy consumption.

- Lack of interaction between thermal and electrical energy supply

In most of the previous studies, cooling, heating and electrical energy demands from buildings were considered separately. For example, envelope insulation and solar thermal collector was adopted to reduce thermal demand and increase thermal energy production, respectively. Meanwhile, PV panel and lighting control were adopted to increase electrical energy production and reduce electricity consumption, respectively. However, there was no approach to determining the distribution of the design area between solar thermal collectors and PV panels. On the other hand, the CCHP system [27] and multi-energy system [28] can provide cooling, heating and electrical energy simultaneously. However, there was no existing retrofitting tool which could evaluate the thermal and electrical energy performance of adopting the CCHP system or multi-energy system in an existing building.

1.3. Novelty and contribution

Based on the three distinct research gaps, the objective of this study is to propose a retrofitting optimisation approach with the integration of life-cycle optimisation and supply-side management. The proposed retrofitting optimisation approach has the following four unique features:

- Considering a combination of passive and active retrofitting options

The passive building retrofitting options consist of various envelope insulation to reduce thermal energy demand and solar conversion systems to generate renewable energy production. Meanwhile, the peak energy shifting capability of heat storage and electricity storage will be investigated. Moreover, the energy-saving performance of active energy devices such as biomass boilers, GSHP and CHP systems will be evaluated.

- Considering the supply-side management of retrofitting energy devices

Based on the year-round variation of heating demand, electricity demand, solar heating production and solar electricity production, the optimal charging/discharging rate of heat and electricity storage, as well as the operating capacity of GSHP and CHP system along different time of the year, will be determined through ant colony optimisation (ACO) algorithm.

- Considering the interaction between thermal and electrical energy supply

The adoption of the GSHP system will result in extra electricity consumption, while the CHP system can supply thermal and electrical energy at the same time. According to the varying ratio of thermal to the electricity demand of the building, the optimal operating capacity allocation among different energy devices will be determined through different periods of the year.

- Interactive retrofitting plan at both design and operating stage

The initial design and actual operating capacity of each energy device will be determined interactively and iteratively to ensure that the design of optimal retrofitting solution can effectively suit its optimal year-round operation.

2. Integrated life-cycle optimisation and supply-side management

The proposed integrated retrofitting optimisation approach aims to define the optimal refurbishment plan to curtail life-cycle energy consumption with effective supply-side management. In this study, the refurbishment plan is mainly chosen from market-available retrofitting materials. For passive retrofitting options, such as envelope insulation, PV panel and solar thermal collector, the achievable energy consumption reduction depends on the retrofitting design and year-round weather data. In this study, passive solar thermal collector is used. Based on solar radiation and water pressure, its heat transfer is driven by natural convention, while no external sources or pumps is needed. For active retrofitting options, like CHP system, biomass boiler, GSHP system, electricity storage and heat storage, their operating performance is determined by the actual operating capacity. Due to the varying energy demand at different periods of the year, the optimal operating plan is critical to ensure optimal energy-saving performance for these active retrofitting devices.

Life-cycle optimisation of retrofitting plans depends on effective supply-side management. In other words, the optimal retrofitting strategy is affected by the actual operating schedule of active energy devices. Therefore, an interactive and integrated optimisation approach is proposed: the **optimal design configuration** and corresponding **optimal operating plan** of retrofitting energy devices are obtained by performing two interrelated optimisation sets. To be more specific, the **optimal design configuration** obtained from the first-set optimisation is referred to as operational constraints in the second-set optimisation. Meanwhile, the **optimal operating plan** resulted from the second-set optimisation forms a part of the objective function in the first-set optimisation. The flowchart of this interactive and integrated retrofitting approach is demonstrated in Fig. 1.

According to our previous research work, wall and roof insulation are the most effective retrofitting approaches in reducing overall life-cycle energy consumption [25]. Therefore, it has already been implemented in the current case study building. This study focuses on

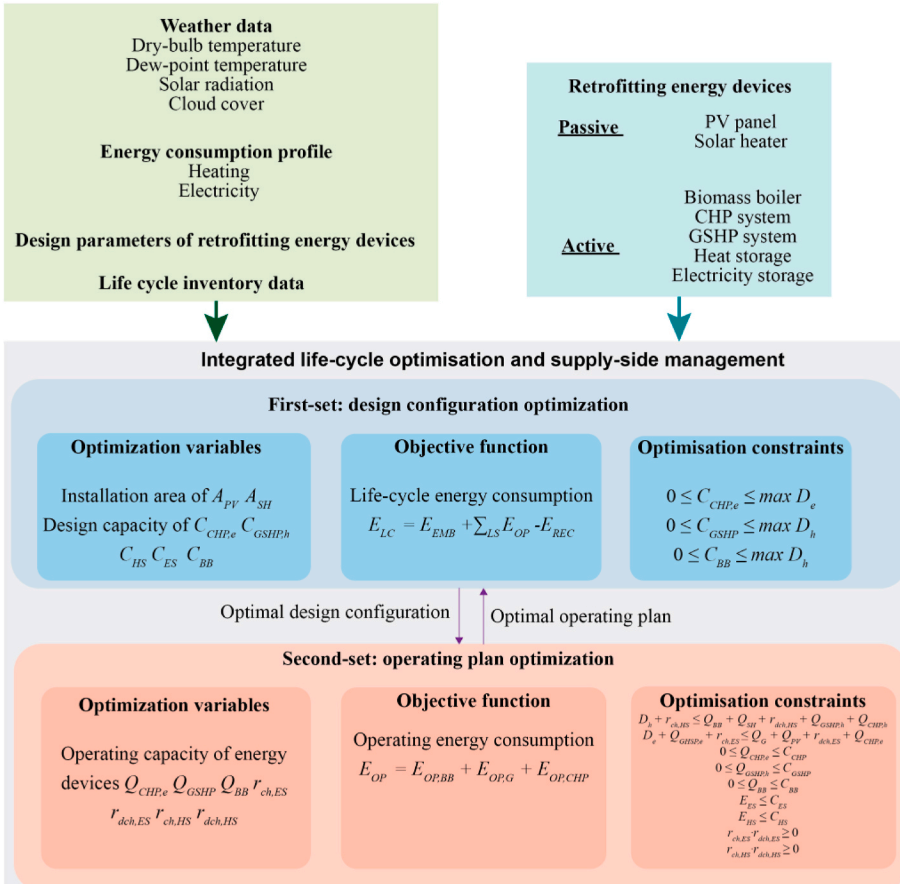


Fig. 1. Flowchart of the proposed interactive retrofitting optimisation approach.

retrofitting energy devices. However, the proposed retrofitting optimisation approach can be easily extended to roof and wall insulation, if needed.

2.1. First-set optimisation

The objective of the first-set optimisation is to determine the optimal design configuration based upon the optimal operating schedule determined by the second-set optimisation.

2.1.1. Decision variables

In the first-set optimisation, the decision variables include the design area of the PV panel A_{PV}, design area of the solar thermal collector A_{SH}, design capacity of the CHP system $C_{CHP,e}$, design capacity of the GSHP system $C_{GSHP,h}$, design capacity of the heat storage C_{HS}, design capacity of the electricity storage C_{ES}, and design capacity of the biomass boiler C_{BB}. The design capacity, also named rated power, refers to the maximum achievable operating capacity, which can be reached when the energy device works at its full load.

2.1.2. Optimisation objective function

The overall optimisation objective is to minimise life-cycle energy consumption, which consists of embodied energy from manufacturing, operating energy consumption during its lifetime, as well as energy recycled during the end-of-life.

$$\min E_{LC} = E_{EMB} + \sum_{LS} E_{OP} - E_{REC} \tag{1}$$

E_{EMB} is the total embodied energy in each retrofitting energy device, which depends upon the real-life inventory data.

$$E_{EMB} = e_{EMB,PV}A_{PV} + e_{EMB,SH}A_{SH} + e_{EMB,CHP}C_{CHP,e} + e_{EMB,GSHP}C_{GSHP,h} + e_{EMB,ES}C_{ES} + e_{EMB,HS}C_{HS} + e_{EMB,BB}C_{BB} \tag{2}$$

e_{EMB} is the embodied energy of each unit retrofitting energy device. E_{OP} is the year-round operating energy consumption, which is determined by the second-set optimisation. E_{REC} is the recyclable energy at the end-of-life for each retrofitting material, which depends on the end-of-life recycle ratio:

$$E_{REC} = R_{REC,PV}e_{EMB,PV}A_{PV} + R_{REC,SH}e_{EMB,SH}A_{SH} + R_{REC,CHP}e_{EMB,CHP}C_{CHP,e} + R_{REC,GSHP}e_{EMB,GSHP}C_{GSHP,h} + R_{REC,ES}e_{EMB,ES}C_{ES} + R_{REC,HS}e_{EMB,HS}C_{HS} + R_{REC,BB}e_{EMB,BB}C_{BB} \tag{3}$$

2.1.3. Optimisation constraints

$C_{CHP,e}$ should not exceed the maximum electrical energy demand, while C_{GSHP} and C_{BB}should not exceed the maximum heating demand D_h. The electricity demand is calculated using the actual measurement of electricity consumption, while the heat demand is determined using the validated TRNSYS simulation model. The detailed calculation method is discussed in Section 4.3. The upper bound of the design capacity is set to avoid over-sizing and profligacy of resources.

$$0 \le C_{CHP,e} \le \max D_e \tag{4}$$

$$0 \le C_{GSHP} \le \max D_h \tag{5}$$

$$0 \le C_{BB} \le \max D_h \tag{6}$$

2.2. Second-set optimisation

Based on the design configuration decided at the first-set optimisation at each iteration, the purpose of the second-set optimisation is to define the optimal operating plan of each energy active device to minimise its operating energy consumption. It is anticipated that each active energy device can operate at its high efficiency as much as possible. It is also expected that heat and electricity storage can effectively move the energy demands from peak time to valley periods.

2.2.1. Decision variables

In the second-set optimisation, the design variables include the operating capacity of $Q_{CHP,e}$, operating capacity of the GSHP system Q_{GSHP}, operating capacity of biomass boiler Q_{BB}, charging rate of heat storage $r_{ch,HS}$, discharging rate of heat storage $r_{dch,HS}$, charging rate of electricity storage $r_{ch,ES}$ and discharging rate of electricity storage $r_{dch,ES}$. The operating capacity refers to the actual energy rate of each device, which depends on its actual load ratio. If the energy device works at its part-load, the operating capacity would be smaller than its design capacity.

2.2.2. Objective function

The purpose of the second-set optimisation is to minimising the year-round operational energy consumption E_{OP} as set in equation (1). As the PV panel and solar thermal collector generate energy from the renewable energy source (i.e., solar), there is no operational energy consumption from them. Electricity storage and heat storage are energy conversion devices, which do not consume primary energy. However, the energy generated from on-site renewables and energy converted through energy devices is considered as optimisation constraints when considering the energy balance between demand and supply, as introduced in Section 2.2.3. Moreover, renewables and energy storage do consume energy during its manufacturing stage, which is considered as embodied energy, as introduced in Section 2.1.2.

It is also assumed that the electricity consumption of GSHP is supplied by the power grid, PV panel or electricity storage. Thus, the equivalent electricity demand is considered as the total building basic electricity demand and electricity consumption of GSHP. Therefore, the operational energy consumption mainly comes from biomass consumption of biomass boiler, primary energy consumption at power grid, as well as biomass consumption of CHP system.

$$E_{OP} = E_{OP,BB} + E_{OP,G} + E_{OP,CHP} \tag{7}$$

2.2.3. Optimisation constraints

Heating and electrical energy demands required by the building should be smaller than energy production from the supply side (i.e., integrated energy system):

$$D_h + r_{ch,HS} \leq Q_{BB} + Q_{SH} + r_{dch,HS} + Q_{GSHP,h} + Q_{CHP,h} \tag{8}$$

$$D_e + Q_{GSHP,e} + r_{ch,ES} \leq Q_{CHP,e} + Q_{PV} + Q_G + r_{dch,ES} \tag{9}$$

The operating capacity of the CHP system, GSHP system and biomass boiler should not be larger than their design capacities:

$$0 \leq Q_{CHP,e} \leq C_{CHP} \tag{10}$$

$$0 \leq Q_{GSHP,h} \leq C_{GSHP} \tag{11}$$

$$0 \leq Q_{BB} \leq C_{BB} \tag{12}$$

Meanwhile, energy stored in heat and electricity storage should not be larger than their respective design capacities:

$$E_{HS} \leq C_{HS} \tag{14}$$

$$E_{ES} \leq C_{ES} \tag{13}$$

Furthermore, the charging and discharging process could not take place at the same time:

$$r_{ch,ES} \cdot r_{dch,ES} \geq 0 \tag{15}$$

$$r_{ch,HS} \cdot r_{dch,HS} \geq 0 \tag{16}$$

2.3. Optimisation approach

Ant colony optimisation (ACO) algorithm is adopted in two sets of optimisation to find out its respective optimal design variables. ACO is inspired by the foraging behaviour of ants [29]. The chemical pheromone trails can help ants to find the shortest route from their nest and food sources; such indirect communication can be regarded as the principle of foraging behaviour [30]. ACO algorithm has the advantage of strong robustness and suitable dispersed calculative mechanism, while it also shows excellent performance in resolving the comprehensive optimisation problem. ACO algorithm has been widely adopted on travelling salesman problems, job scheduling problems, structural and concrete engineering problems, digital image processing, electrical engineering, clustering and routing algorithms [31].

Based on the transition probability and total pheromone in the region, an updated pheromone trail can be obtained to move ants around in the search space [32]. At every iteration, the ACO algorithm would generate global ants and calculate corresponding fitness. It will then update the pheromone and edge of weak regions. If the fitness value is improved, the local ants would be moved to better areas. If there is no improvement in fitness, a new random search direction will be selected. The ant pheromone will also be updated and evaporated accordingly [33].

$$P_k(t) = \frac{\rho_k(t)}{\sum_{j=1}^{n} \rho_j(t)} \tag{17}$$

where n is the number of global ants and $\rho_k(t)$ is the total pheromone at area k. Each pheromone is updated according to the evaporation rate:

$$\rho_j(t+1) = (1-r)\rho_j(t) \tag{18}$$

where r is the pheromone evaporation rate. The process flow for ACO is shown in Fig. 2.

2.4. Materials and methods

In order to test the reproducibility of the proposed life-cycle optimisation and supply-side management building retrofitting approach, a

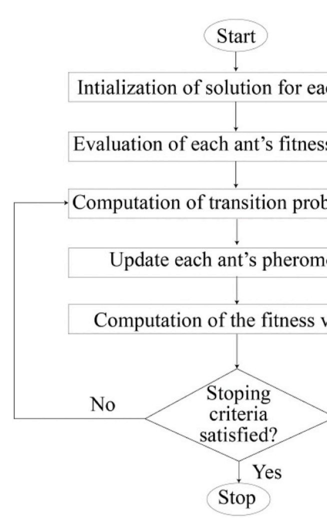


Fig. 2. Process flow of ACO.

real-life office building is adopted as the case study. The detailed building information, associated weather profiles, corresponding building heating and electrical energy demands, design parameters of retrofitting energy devices, and life-cycle inventory data are summarised in Section 4. These types of information would be adopted as input datasets for the retrofitting optimisation approach. Meanwhile, to get the operating capacity of each retrofitting energy device, thermodynamic models of the office building and associated energy devices are presented in Section 3. Based on these thermodynamic models and corresponding information of the case study building, the obtained retrofitting solution can be reproduced.

3. Thermodynamic model of building and energy devices

Thermodynamic models of building and retrofitting energy devices are developed using first-principle equations.

3.1. Thermal model of the building

Building thermal load indicates the total heat required to be removed from the building to bring it to the indoor design condition. Building thermal load includes external heat gain Q_{ext} and internal heat gain Q_{int}:

$$D_h = Q_{ext} + Q_{int} \tag{19}$$

External heat gain Q_{ext} is composed of infiltration heat gain Q_{inf}, ventilation heat gain Q_{vent}, transmission heat gain Q_{trans} and solar heat gain Q_{solar}.

$$Q_{ext} = Q_{inf} + Q_{vent} + Q_{trans} + Q_{solar} \tag{20}$$

Meanwhile, internal heat gain is caused by occupant Q_o, lighting Q_l and office equipment Q_{eq}.

$$Q_{int} = Q_o + Q_1 + Q_{eq} \tag{21}$$

3.2. PV panel

Electricity can be generated from PV panels. The electricity generation rate depends on the global solar radiation as well as the design area and electrical efficiency of PV panels.

$$Q_{PV} = G \cdot A_{PV} \cdot \eta_{PV} \tag{22}$$

$$\eta_{PV} = \eta_{PV,n}\left[1 + \varepsilon_T\left(T_{db} - T_{PV,ref}\right)\right]\left[1 + \varepsilon_\varphi\left(G - G_{PV,ref}\right)\right] \tag{23}$$

3.3. Solar thermal collector

Heating energy can be generated from the solar thermal collector. Thermal power production depends on global solar radiation.

$$Q_{SH} = G \cdot A_{SH} \cdot \eta_{SH} \tag{24}$$

$$\eta_{SH} = \eta_{SH,n} - \alpha \times \left(T_{DB} - T_{SH,ref}\right)/G \tag{25}$$

3.4. Biomass boiler

The biomass boiler has higher energy efficiency, while it consumes lower embodied energy compared to the traditional gas boiler. Its operating energy consumption depends on its operating efficiency.

$$E_{OP,BB} = Q_{BB}/\eta_{BB} \tag{26}$$

3.5. CHP system

The CHP system is fuelled by biomass, which has higher energy efficiency and lower embodied energy than conventional natural gas. The thermodynamic model of CHP system developed in our previous research [34] is adopted. The operating energy consumption of CHP system depends on its operating electrical efficiency, while its operating thermal efficiency decides the recoverable thermal energy. The operating electrical and thermal efficiency is affected by its part-load-ratio (PLR):

$$E_{OP,CHP} = \frac{Q_{CHP,e}}{\eta_{CHP,e}} \tag{27}$$

$$\eta_{CHP,e} = \eta_{CHP,e,n}\left(-0.0001591PLR_{CHP}^2 + 0.024PLR_{CHP} + 0.1904\right) \tag{28}$$

$$Q_{CHP,h} = \eta_{CHP,h} E_{op,CHP} \tag{29}$$

$$\eta_{CHP,h} = 8.556e^{-0.2619 \cdot PLR_{CHP}^2} + 18.91e^{0.001194 \cdot PLR_{CHP}} \tag{30}$$

3.6. GSHP system

GSHP can transfer heat from the ground soil into buildings. Earth can absorb solar energy and maintain the heat at around 10 °C throughout the winter. The GSHP uses a ground heat exchange to transfer such ground heat to building heating demand. The electrical energy consumption of the GSHP system depends on its operating coefficient of performance (COP).

$$Q_{GSHP,e} = Q_{GSHP,h}/COP_{GSHP} \tag{31}$$

3.7. Energy storage

The amount of heating and electrical energy stored in the heat and electrical storage depends on the corresponding charging rate, discharging rate, charging efficiency and discharging efficiency.

$$E_{HS,j+1} = E_{HS,j} + r_{ch,HS}\eta_{ch,HS} - r_{dch,HS}/\eta_{dch,HS} \tag{32}$$

$$E_{ES,j+1} = E_{ES,j} + r_{ch,ES}\eta_{ch,ES} - r_{dch,ES}/\eta_{dch,ES} \tag{33}$$

4. Case study

To evaluate the performance of the interactive retrofitting optimisation approach, it is tested on a real-world office building. The building information, historical weather profile, historical building energy demand, design parameters of energy devices, energy production from renewable energy devices and life-cycle inventory data are summarised in this section.

4.1. Building information

The retrofitting performance of the high-rise Costain House is evaluated. Costain House is a representative medium-sized office building located at Manchester, the United Kingdom. Its floor area, external wall area and window size are 1428 m^2, 697 m^2 and 1331 m^2, respectively. The floor plan is of L type, as shown in Fig. 3. At the current state, space and water heating are provided by a conventional gas heater, while electricity is supplied by the power grid.

4.2. Weather profile

To investigate the changes in building thermal demands before and after retrofitting, the developed TRNSYS model is adopted to simulate the building operation. The historical weather profiles recorded at Manchester in the year 2019 are adopted as inputs to the TRNSYS simulation model. The historical weather profiles include outdoor temperature, dew-point temperature, cloud opacity and global solar radiation. The highest outdoor temperature, dew-point temperature and global solar radiation are identified in July, while their lowest values are found in January and December. The cloud cover varies all over the year.

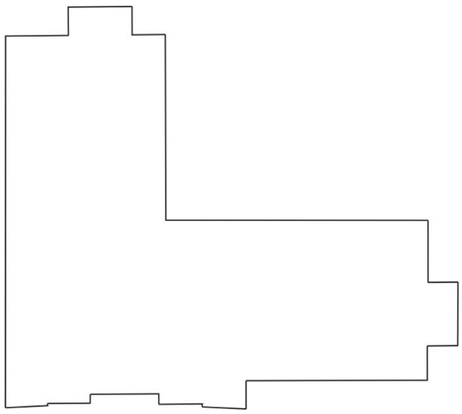


Fig. 3. Floor plan of the office building.

4.3. Building energy demands

The historical electricity consumption is collected at the time step of half-an-hour. After data collection, it is processed at the hourly time step and adopted as the electricity demand. Meanwhile, the monthly natural gas usage is estimated from bills. However, hourly building heating demand is important in supply-side management. Therefore, TRNSYS18 is adopted to simulate the building operation to obtain hourly heating demands [35]. Type 56 building thermal model is developed based upon fundamental heat transfer equations and has been widely utilised for building energy simulation [36,37]. To verify the hourly heating demand obtained from TRNSYS 18 simulation, the monthly gas consumption is obtained and compared to the collected historical gas usage. Due to higher dry-bulb, dew-point temperature and solar radiation in the summer, the heating demand is relatively lower.

4.4. Design parameters of retrofitting energy devices

The design parameters for the PV panel, solar thermal collector, biomass boiler, biomass CHP system, GSHP system, heat storage and electricity storage are summarised in Table 1. The nominal electricity efficiency of the CHP system is determined by its design capacity.

4.5. Life cycle inventory data

Life cycle inventory data was collected according to ISO 14,040 standard [45]. Primary energy consumed during the manufacturing and production stage of retrofitting materials is regarded as embodied energy. The inventory data is collected from various sources. The inventory data of various energy devices are summarised in Table 2.

Table 1
Design performance parameters.

Energy devices	Design parameters	Unit	Value
PV panel [38]	Nominal efficiency$\eta_{PV,n}$	%	12
	Reference temperature	°C	25
	Reference radiation G_{ref}	kJ/h m^2	3600
	Correction coefficient of temperature ε_T	–	−0.005
	Correction coefficient of solar radiation ε_φ	–	0.000025
Solar thermal collector [39]	Nominal efficiency $\eta_{SC,n}$	%	44
Biomass boiler [40]	Thermal efficiency	%	92
CHP system [41]	Nominal electrical efficiency	–	$0.0194\ln(C_{CHP})+0.2321$
GSHP system [42]	Coefficient of Performance	–	3.2
Heat storage [43]	Efficiency of energy charge	%	90
	Efficiency of energy discharge	%	90
Electricity storage [44]	Efficiency of energy charge	%	90
	Efficiency of energy discharge	%	90

5. Life-cycle performance under different retrofitting options

Different combinations of retrofitting options are investigated to assess retrofitting performance. To learn the energy performance of each retrofitting energy device, four reference situations are investigated to gain insights into the effects of changing design capacity on the embodied energy and life-cycle energy consumption. The effects of the end-life recycle ratio of retrofitting energy devices are also investigated. More importantly, other two situations are adopted to assess the effectiveness of the proposed retrofitting optimisation approach.

5.1. Situation 1: solar thermal collector and heat storage

In Situation 1, solar thermal collector and heat storage are collectively used to satisfy the building heating demand, while the existing gas boiler is abandoned owing to its high energy consumption. The relationship between the design capacity of heat storage and the design area of the solar thermal collector is shown in Fig. 4. With the design area of the solar thermal collector increases from 1500 m^2 to 6000 m^2, the volume of heat storage decreases from 1745 m^3 to 447 m^3. Due to the fact that greater heating demand can be satisfied by the solar thermal collector, a smaller volume of heat storage is needed to shift the peak heating load.

When the design area of the solar thermal collector is 2000 m^2, the actual heating energy from the solar thermal collector, the charging rate and discharging rate of heat storage are shown in Fig. 5. When heating power from the solar thermal collector is lower than the actual heating energy demand (e.g. during the first 87 h of the week), heat storage is discharged to satisfy actual heating demand. When heating power from the solar thermal collector is higher than the actual heating demand (e.g. during the 130th-134th h, and 153rd-158th h of the week), the excessive heating energy can be charged to store in the heat storage.

Life-cycle energy consumption at different recycle ratios of heat storage, and solar thermal collector (i.e., 0.1, 0.5 and 0.9) are summarised in Fig. 6. When the recycle ratios of solar thermal collector and heat storage are the same, respectively, no matter if it is 0.1, 0.5 or 0.9, the life-cycle energy consumption decreases with the rise of design area of solar thermal collector. It reaches its topmost when the design area is 2500 m^2. After that, life-cycle energy consumption would decrease with increasing design area of solar thermal collector. Moreover, when $R_{HS} = 0.1$ and $R_{SH} = 0.5$ or 0.9, or when $R_{HS} = 0.5$ and $R_{SH} = 0.9$, the life-cycle energy consumption decreases with the increasing design area of solar thermal collector. Otherwise, when $R_{HS} = 0.9$ and $R_{SH} = 0.1$ or 0.5, or when $R_{HS} = 0.5$ and $R_{SH} = 0.1$, the life-cycle energy consumption increases with the increase area of solar thermal collector.

Since the heating demand is fully supported by solar thermal collector and heat storage, there is no energy consumption during its operating stage. When end-life recycle of material is not considered, the

Table 2
Summary of inventory data.

Energy devices	Embodied energy (MJ)
Electricity imported from power grid (per kWh) [46]	9.0
Biomass (per kWh) [46]	0.455
PV panel (per m^2) [47]	3266.6
Solar thermal collector (per m^2) [48]	3000
GSHP (per kW) [49]	17000
CHP system (per kW) [50]	138800
Biomass boiler (per kW) [51]	57005.2
Heating storage (per m^3) [52]	70457
Electricity storage (per kW) [53]	1800

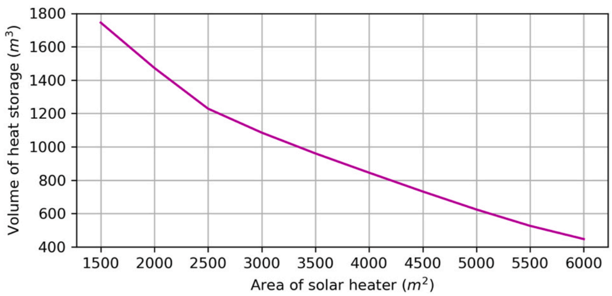


Fig. 4. Relationship between design capacity of heat storage and design area of solar thermal collector.

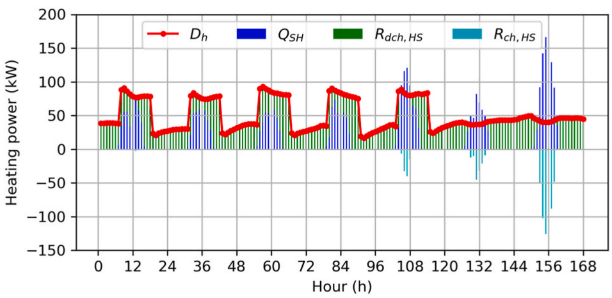


Fig. 5. Heat power distribution between solar thermal collector and heat storage.

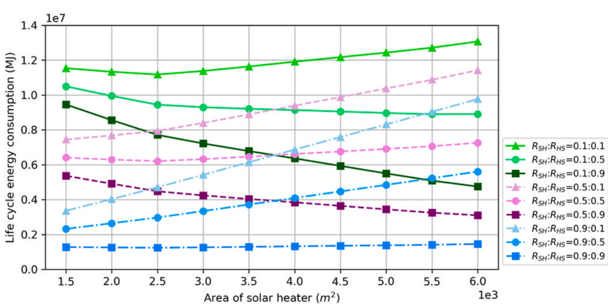


Fig. 6. Life cycle energy consumption at diverse recycle ratios of solar heater and heat storage.

distribution of embodied energy between solar thermal collector and heat storage is shown in Fig. 7. As shown in Fig. 4, the design capacity and associated embodied energy of heat storage decreases with the increasing design area of solar thermal collector. Nevertheless, the minimum total embodied energy is identified when the design area of the solar thermal collector is 2500 m^2.

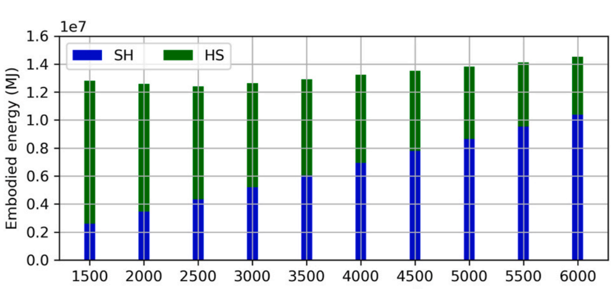


Fig. 7. Embodied energy distribution between solar thermal collector and heat storage.

5.2. Situation 2: PV panel and electricity storage

In Situation 2, PV panel and electricity storage are collectively used to supply electrical energy. The relationship between the design capacity of electricity storage and design area of PV panel is shown in Fig. 8. With the design area of PV panel increasing from 12800 m^2 to 50000 m^2, the design capacity of electricity storage decreases from 2.22 $\times$ 10^5 kWh to 8604 kWh.

When the design area of the solar thermal collector is 15,000 m^2, the actual electrical energy production from the PV panel, the charging rate and discharging rate of electricity storage is shown in Fig. 9. When electricity production from PV panels is lower than the electricity demand, electricity storage is discharged to supplement the actual electrical energy demand. When electrical power from the PV panel is larger than the electricity demand, the excess electrical energy can be charged to store in the electricity storage.

Life-cycle energy consumption at different recycle ratios of electricity storage and PV panel (i.e., 0.1, 0.5 and 0.9) is summarised in Fig. 10. Due to the high embodied energy of electricity storage, its capacity has a substantial effect on life-cycle energy. When the recycle ratio of electricity storage is not higher than that of the PV panel, the life-cycle energy consumption declines with the increasing area of PV panel. However, the design area of PV panels may be limited by actual available space. When the recycle ratio of electricity storage is higher than that of PV, the life-cycle energy will increase when the design area of the PV panel is larger than 35,000 m^2. It is mainly owing to the excessive electrical energy generated by the PV panel, especially during summer.

Since the electrical energy demand is fully supported by PV panels and electricity storage, there is no energy consumption during its operating stage. When end-life recycle of material is not considered, the distribution of embodied energy between PV panel and electricity storage is shown in Fig. 11. Due to the high embodied energy of electricity storage, the total life-cycle energy of PV panels and electricity storage decreases with the decreasing capacity of electricity storage.

5.3. Situation 3: solar thermal collector, heat storage and biomass boiler

In Situation 3, the solar thermal collector, heat storage and biomass boiler are collectively used to satisfy heating demand. When the recycle ratio of both heat storage, and the solar thermal collector is 0.5, the life span of each component is 50, the life-cycle energy consumption at different design areas of the PV panel (i.e., 2000 m^2, 2500 m^2 and 3000 m^2) is shown in Fig. 12. The life-cycle energy consumption grows with the rise of the design capacity of a biomass boiler. When the design area of the solar thermal collector is 2000 m^2, the life-cycle energy consumption is the largest. When the design capacity of biomass boiler is lower than 6 kW, the system with the solar thermal collector area of 2500 m^2 has larger life-cycle energy consumption than that with the solar thermal collector area of 3000 m^2, and vice versa.

The relationship between the design capacity of heat storage and biomass boiler at different design areas of the PV panel (i.e., 2000 m^2, 2500 m^2 and 3000 m^2) is shown in Fig. 13. The design capacity of heat storage increases with the decrease of design area of the solar thermal

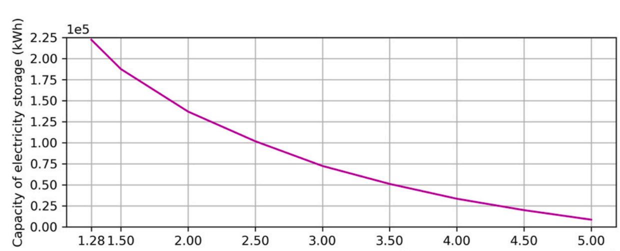


Fig. 8. Relationship between the design capacity of electricity storage and design area of PV panel.

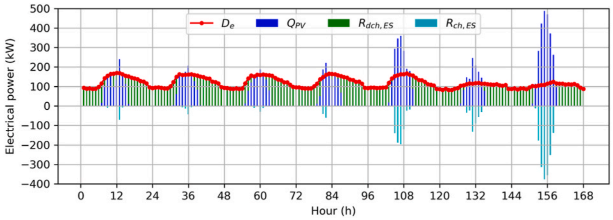


Fig. 9. Electrical power distribution between PV panel and electricity storage.

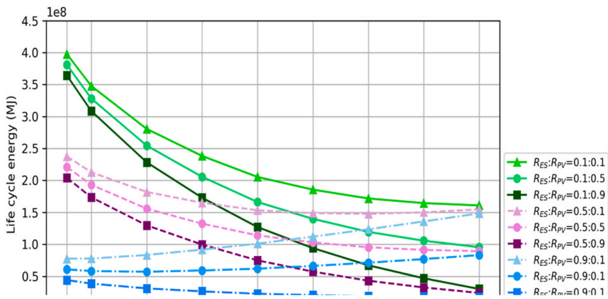


Fig. 10. Life-cycle energy consumption at different recycle ratios of electricity storage and PV panel.

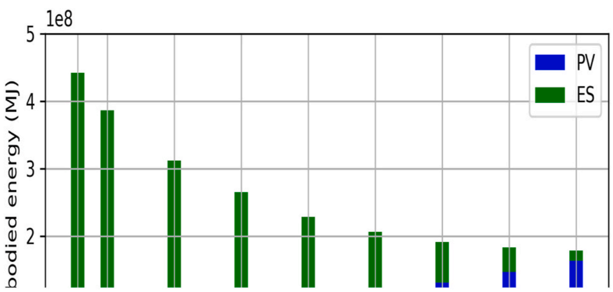


Fig. 11. Embodied energy distribution between PV panels and electricity storage.

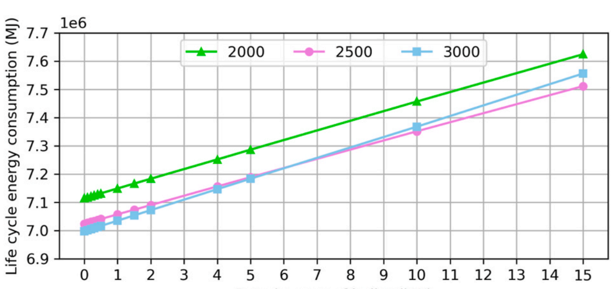


Fig. 12. Life cycle energy consumption at different design areas of PV panel.

collector and the decrease of the design capacity of the biomass boiler.

When the recycle ratio of heat storage, biomass boiler and the solar thermal collector is 0.5, the life span of each component is 50, the life-cycle energy consumption contribution from different components is shown in Fig. 14. Three different cases are investigated, with the design capacity of biomass boiler set at 0, 1 kW and 15 kW, respectively. The most considerable contribution of life-cycle energy consumption is from the heat storage, followed by the embodied energy of solar thermal collector as well as embodied energy and primary energy consumption from the biomass boiler.

Life-cycle energy consumption at different recycle ratios of heat

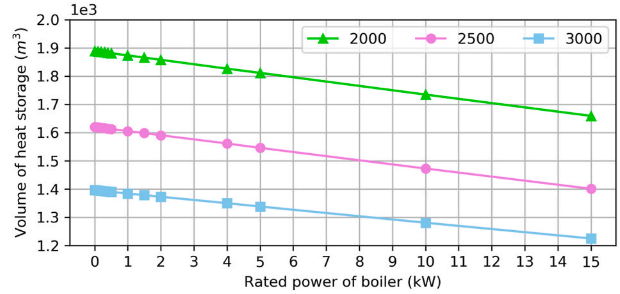


Fig. 13. Relationship between design capacity of heat storage and biomass boiler at different design areas of the solar thermal collector.

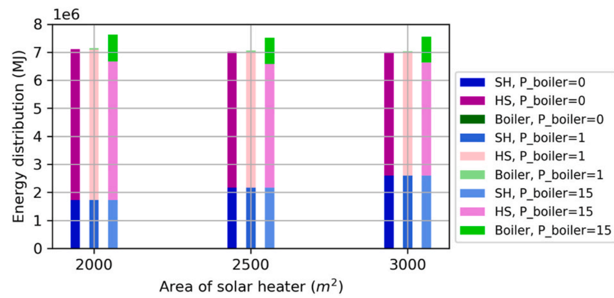


Fig. 14. Energy composition of solar thermal collector, heat storage and a biomass boiler.

storage, and solar thermal collector (i.e., 0.1, 0.5 and 0.9) is summarised in Fig. 15. When the recycle ratio of heat storage is 0.1, the life-cycle energy consumption is almost consistent at a different rated power of biomass boiler. When the recycle ratio of heat storage is 0.5 or 0.9, the life-cycle energy consumption rises with the growth of design capacity of biomass boiler.

The equivalent annual life cycle energy consumption at different life spans (i.e., 30, 40 and 50 years) is shown in Fig. 16. The equivalent annual life cycle energy consumption increases with the decrease of life span and increase of design capacity of biomass boiler.

5.4. Situation 4: PV panel, electricity storage and power grid

In Situation 4, PV panel and electricity storage are collectively used to satisfy the electricity demand, while electricity can also be imported from the power grid when necessary. When the recycle ratio of electricity storage and PV panels is 0.5, the life span of each component is 50 years, the life-cycle energy consumption at different limited electricity importation rates (i.e. 2, 5, 10, 20, 30, 40 and 50 kW) is shown in Fig. 17. When the limited electricity importation rate is 50 kW, the lowest life-cycle energy consumption is identified when the design area of the PV panel is 40,000 m^2. When the limited electricity importation rate is

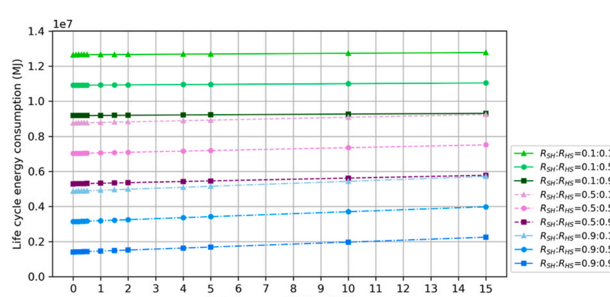


Fig. 15. Life cycle energy consumption at different recycle ratios of solar heater and heat storage.

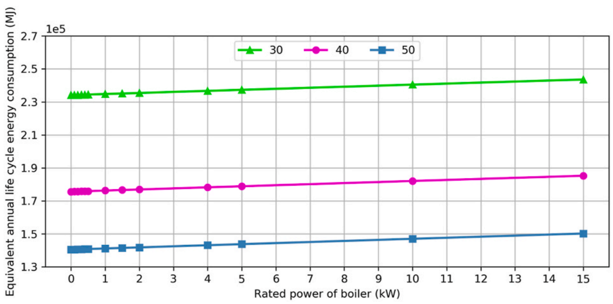


Fig. 16. Life cycle energy consumption at different life span.

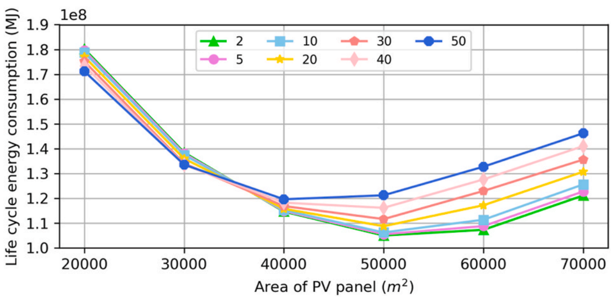


Fig. 17. Life cycle energy consumption at different limited electricity importation rate.

lower than 50 kW, the lowest life-cycle energy consumption is identified when the design area of the PV panel is 50,000 m^2. When the design area of the PV panel is 20,000 m^2, the life-cycle energy consumption is relatively high (i.e., 1.7 × 10^8–1.8 × 10^8 MJ) due to the high embodied energy of electricity storage.

When the limited electricity importation rate is 2 kW and life span is 50 years, life-cycle energy consumption at different recycle ratios of electricity storage and PV panel (i.e., 0.1, 0.5 and 0.9) are summarised in Fig. 18. The recycle ratio of electricity storage has a larger effect on the life-cycle energy consumption than that of the PV panel. When the recycle ratio of electricity storage is 0.1 or 0.5, the life-cycle energy consumption decreases with the increase of PV panel area, while the lowest life-cycle energy consumption is identified when PV panel area is around 40,000–60,000 m^2. When the recycle ratio of electricity storage is 0.9, the life-cycle energy consumption would increase with the increase of PV panel area.

When the limited electricity importation rate is 2 kW, recycle ratio of electricity storage and PV panel is 0.5, the equivalent annual life cycle energy consumption at different life span (i.e., 30, 40 and 50 years) is shown in Fig. 19. The equivalent annual life cycle energy consumption increases with the decrease of life span.

The relationship between the design capacity of electricity storage and design area of PV panels at different limited electricity importation rate (i.e., 2, 5, 10, 20, 30, 40 and 50 kW) is summarised in Fig. 20. The design capacity of electricity storage decreases with the increase areas of PV panels and electricity importation rate. When the area of PV panels is 70,000 m^2, the required design capacity of electricity storage is similar among different limited electricity importation rates.

When the recycle ratio of PV panel and electricity storage is 0.5, while the life span of each component is 50, the energy consumption contribution from PV panel, electricity storage and power grid are shown in Fig. 21. With the increasing design area of PV panel, the embodied energy of PV panel increases, while the embodied energy of electricity storage and operating primary energy consumption decreases.

5.5. Heat storage, electricity storage, PV panel, solar thermal collector and GSHP system

The proposed retrofitting optimisation approach is adopted to select the optimal combination of energy devices among heat storage, electricity storage, PV panel, solar thermal collector and GSHP system. It is expected that GSHP can supplement part of the heating demand using soil energy. The optimal design configuration of both passive retrofitting options (i.e., PV panel and solar thermal collector) and active energy devices (i.e., GSHP, heat storage and electricity storage) obtained from the first-set optimisation is summarised in Table 3. The effects of different end-life recycle ratios of solar thermal collector, GSHP and heat storage are investigated, while the life span of the retrofitting energy devices remains at 50 years. It is seen that the different end-life recycle ratios would result in different design capacities of each retrofitting device. Especially when the recycle ratio of GSHP is 0.1, the design area of the solar thermal collector and design capacity of heat storage would be much higher than those in other cases.

Life-cycle energy consumption at different cases is summarised in Table 4. As it can be seen, the highlighted value is the smallest among the row. It indicates that the smallest life-cycle energy consumption does achieve at corresponding end-of recycle ratios. For example, the smallest life-cycle energy consumption 1.08 × 10^8 kWh is obtained when the end-of-life recycle ratios of solar thermal collector, GSHP and heat storage are 0.9, 0.5 and 0.5, respectively. The life-cycle energy consumption is larger in other cases.

The optimal operating plan is illustrated in Fig. 22, which indicates the effective supply side management of different retrofitting energy devices. During the daytime, the electricity is mainly provided by the PV

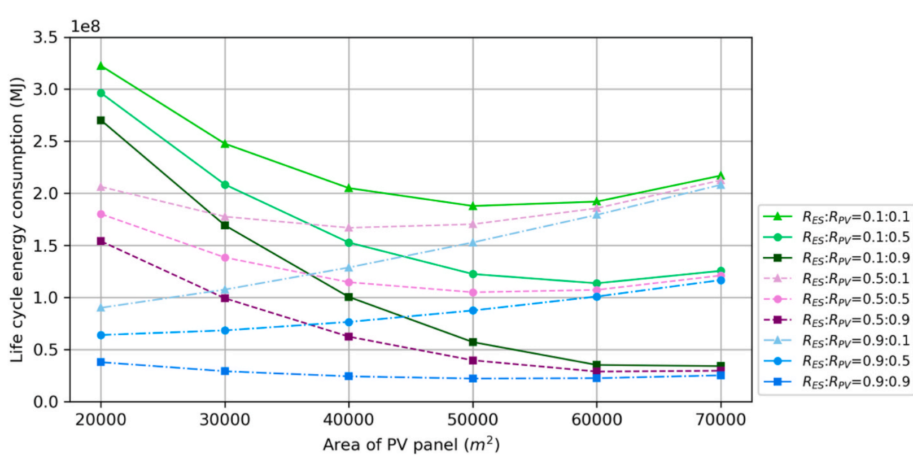


Fig. 18. Life cycle energy consumption at different recycle ratios of electricity storage and PV panel.

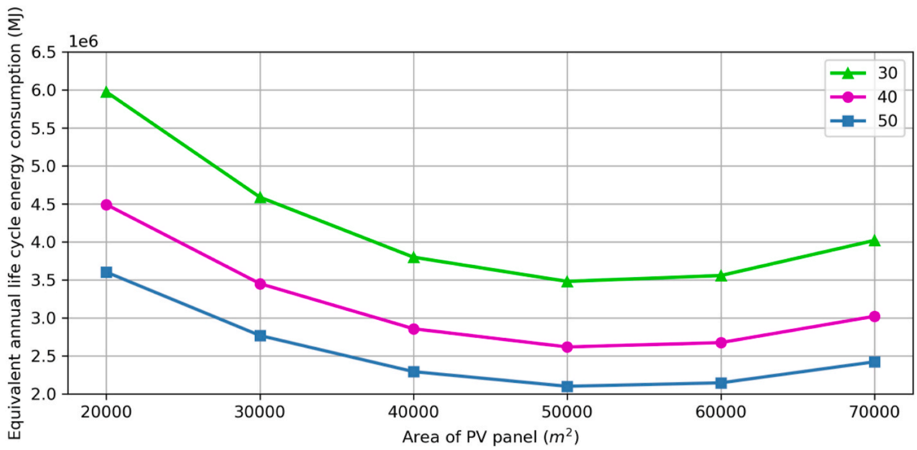


Fig. 19. Equivalent annual life cycle energy consumption at different life span.

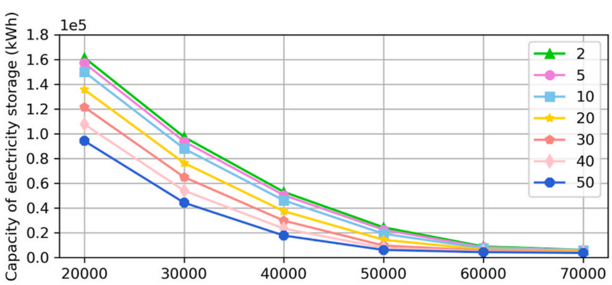


Fig. 20. Relationship between the capacity of electricity storage and PV panel areas at different limited electricity importation rate.

panel when solar radiation is sufficient, while the excess electricity generated by the PV panel is used to charge the electricity storage. During the night, electricity storage is discharged to satisfy the electricity demand since there is no available electricity production from the PV panel. In summer, the heating demand is relatively low, while thermal output from the solar thermal collector is relatively high; thus, the excessive heating energy generated by the solar thermal collector is adopted to charge the heat storage. On the contrary, in winter, the building heating demand is large, while thermal energy from the solar thermal collector is low. Therefore, GSHP is adopted while heat storage is discharged to supplement the heating demand. It is also noticed that the equivalent electricity demand is different among different cases, especially in winter period. It is due to the different operating status of GSHP. This also demonstrates that the proposed retrofitting approach can consider the interaction between heating and electricity supply.

5.6. Heat storage, electricity storage, PV panel, solar thermal collector and CHP system

In Situation 6, the proposed retrofitting optimisation approach is adopted to select the optimal combination of both passive retrofitting options (i.e., PV panel and solar thermal collector) and active energy devices (i.e., CHP system, heat storage and electricity storage). The optimal design configuration from the first-set optimisation is summarised in Table 5. The effects of different end-life cycle ratios of electricity storage, CHP system and PV panel are investigated, while the life span of the retrofitting energy devices remains at 50 years. It is seen that the different end-life recycle ratios would result in different design capacities of each retrofitting device. Especially when the recycle ratio of

Table 3
The optimal design configuration from the first-set optimisation.

Cases	1	2	3	4	5	6	7
$R_{rec,SH}$	0.9	0.5	0.1	0.5	0.5	0.5	0.5
$R_{rec,\ GSHP}$	0.5	0.5	0.5	0.9	0.1	0.5	0.5
$R_{rec,HS}$	0.5	0.5	0.5	0.5	0.5	0.1	0.9
C_{GSHP} (kW)	80	95	90	100	0	80	90
A_{SH} (m^2)	400	160	150	130	2500	200	190
A_{PV} (m^2)	38000	35000	36000	35000	37000	36000	35000
V_{HS} (m^3)	646	447	538	335	1620	712	500
C_{ES} (kWh)	42704	84243	49257	54161	64438	47286	52188

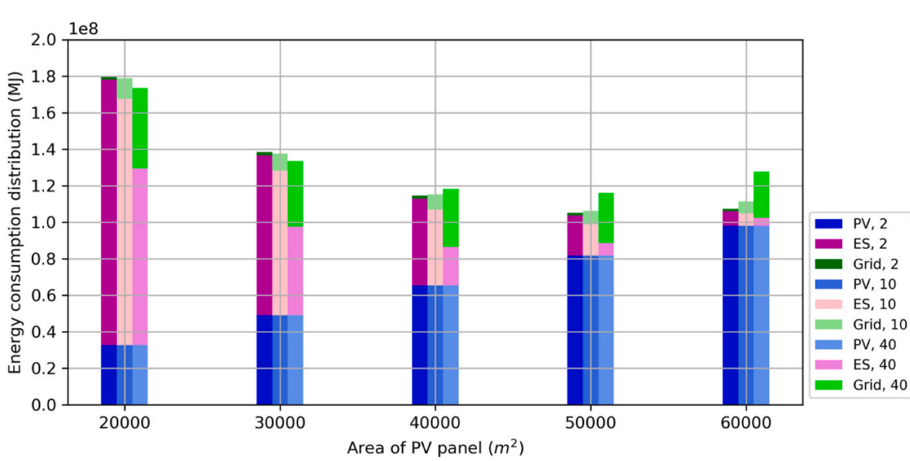
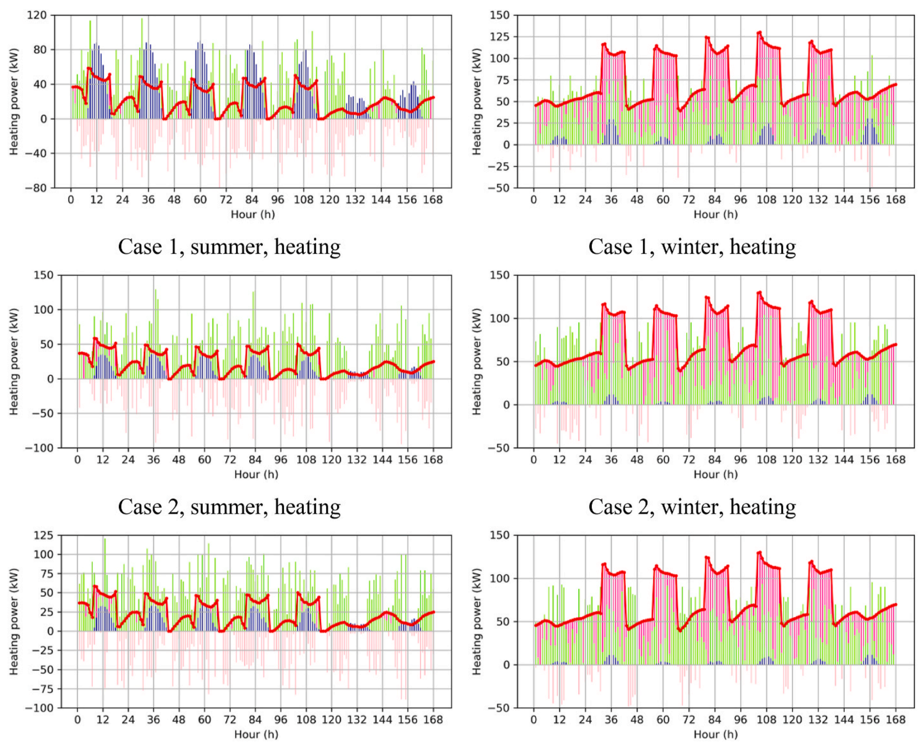


Fig. 21. Energy composition of PV panel, electricity storage and power grid.

Table 4
Life-cycle energy consumption in different cases.

	Recycle ratio			Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
	Solar thermal collector	GSHP	Heat storage							
Life-cycle energy consumption ($\times 10^8$ kWh)	0.9	0.5	0.5	1.08	1.10	1.14	1.11	1.13	1.12	1.13
	0.5	0.5	0.5	1.18	1.15	1.17	1.18	1.16	1.17	1.16
	0.1	0.5	0.5	1.24	1.23	1.19	1.22	1.17	1.21	1.18
	0.5	0.9	0.5	1.17	1.13	1.13	1.11	1.14	1.14	1.14
	0.5	0.1	0.5	1.20	1.19	1.21	1.21	1.18	1.20	1.19
	0.5	0.5	0.1	1.14	1.13	1.14	1.16	1.14	1.10	1.13
	0.5	0.5	0.9	1.20	1.18	1.20	1.21	1.20	1.21	1.17



Case 1, summer, heating
Case 1, winter, heating
Case 2, summer, heating
Case 2, winter, heating
Case 3, summer, heating
Case 3, winter, heating

Fig. 22. Optimal operating plan of each retrofitting energy device.

electricity storage is 0.9, the design capacity of electricity storage would be much higher (i.e., 148622 kWh) while the design area of the PV panel is much lower (i.e., 14000 m^2).

The life-cycle energy consumption at different cases is summarised in Table 6. As it can be seen, the highlighted value is the smallest among the row. It indicates that the smallest life-cycle energy consumption does achieve at corresponding end-of recycle ratios. For example, the smallest life-cycle energy consumption 0.73 $\times$ 10^8 kWh is obtained when the end-of-life recycle ratios of solar thermal collector, CHP system, and heat storage are 0.9, 0.5 and 0.5, respectively. The life-cycle energy consumption is larger in other cases.

The optimal operating plan is illustrated in Fig. 23 which indicates the effective supply-side management of both passive and active retrofitting energy devices. During the daytime, the electricity is mainly provided by the PV panel when solar radiation is sufficient, while the excess electricity generated by the PV panel is used to charge the electricity storage. If the electricity production from the PV panel is insufficient to satisfy electricity demand, the CHP system and electricity storage will work cooperatively to satisfy electricity demand. In summer, the heating demand is relatively low, while thermal production from the solar thermal collector is relatively high; thus, the excessive heating energy generated by the solar thermal collector is adopted to charge the heat storage. During other periods, if the thermal production from the solar thermal collector is not sufficient to satisfy the heating demand, CHP system and heat storage would work cooperatively to meet building heating demand. The CHP system is adopted to provide heating and electrical energy simultaneously. Thus the proposed retrofitting approach can consider the interaction between heating and

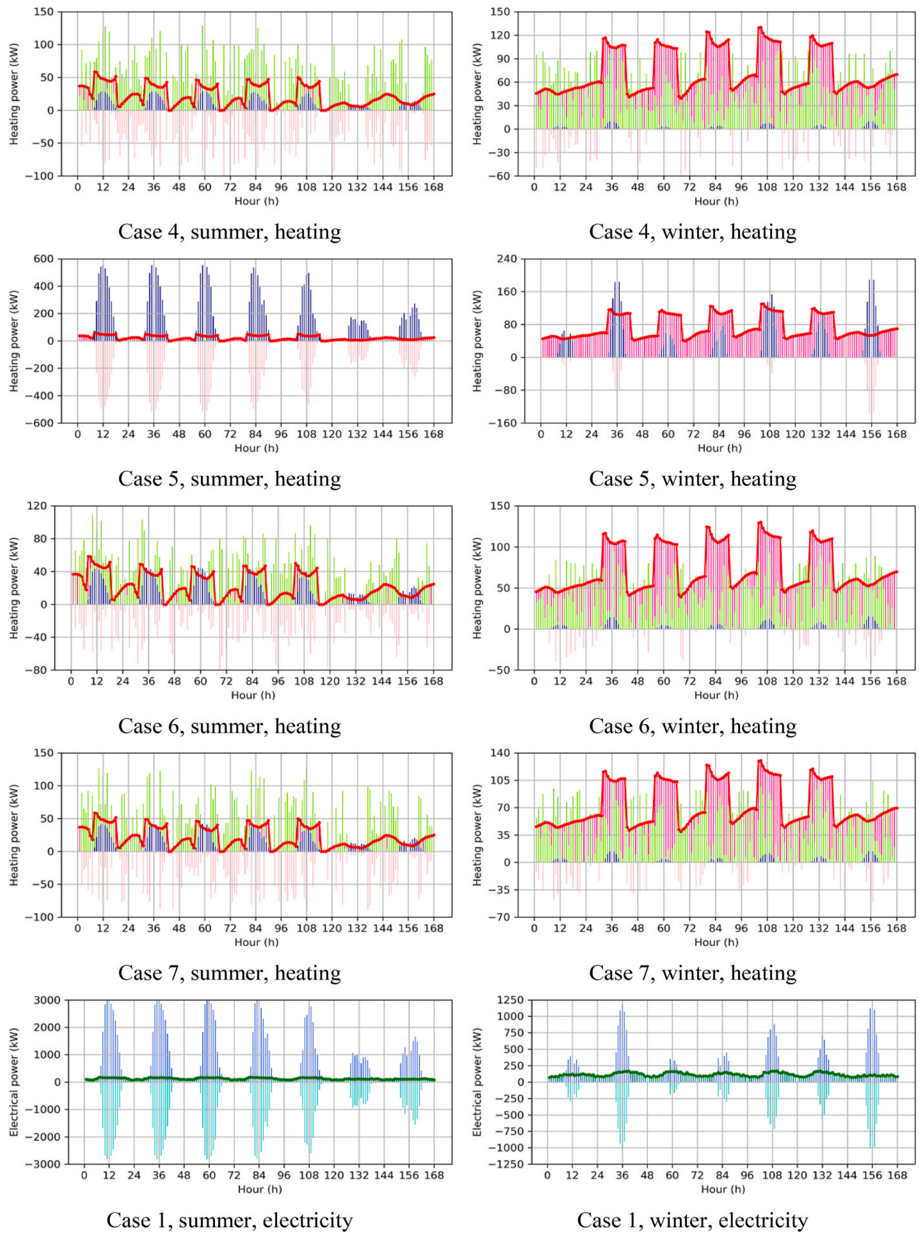


Fig. 22. (*continued*).

electricity supply effectively.

5.7. Reproducibility discussion

In this study, a real-life office building in Manchester, the United Kingdom, is adopted for the case study. The results presented in Sections 5.1-5.4 are based on deterministic and fundamental equations. Therefore, the exact same set of results could be obtained if the same building and input datasets were adopted. Meanwhile, the results presented in Sections 5.5-5.6 are based upon ACO optimisation. Although ACO optimisation is based upon stochastic solution construction procedures, similar solutions could be obtained while running the ACO algorithm several times. This should demonstrate the reproducibility of the proposed retrofitting approach. It is also expected that similar optimal retrofitting solutions could be identified for different sizes of office buildings.

6. Conclusion

To realise the aim of climate neutrality by 2050, it is vital to decrease energy consumption from a life-cycle point of view. In this study, a novel building retrofitting approach is proposed through the integration of life-cycle optimisation and supply-side management. It is an interactive two-set optimisation approach aimed at minimising overall life-cycle energy consumption through determining the optimal **design configuration** and **operating plan** of retrofitting energy devices. In this section, the innovation points of the proposed retrofitting approach, the main findings through the case studies, as well as the suggestions for future work are summarised.

6.1. Innovation points

There are three innovation points of the proposed retrofitting approach:

- Considering a combination of passive and active retrofitting options

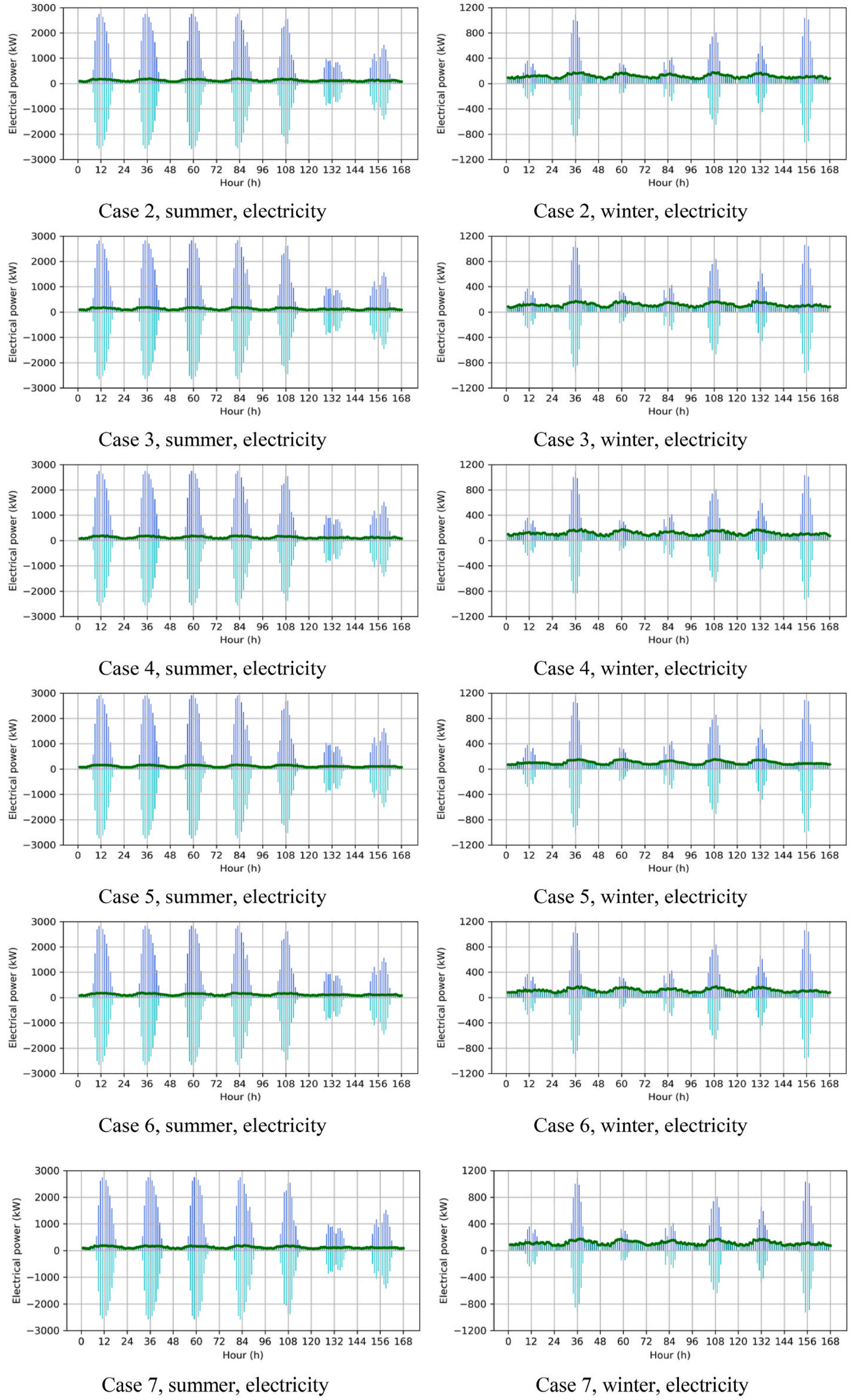


Fig. 22. (*continued*).

The retrofitting options include both passive solutions (i.e., envelope insulation, roof insulation, PV panel, solar thermal collector) and active solutions (i.e., biomass boiler, GSHP system, CHP system, electricity storage and heat storage). Wall insulation and roof insulation are adopted as fundamental retrofitting options. In the first-set optimisation, the design area of passive solutions such as PV panel and solar thermal collector is determined, along with the design capacity of active solutions, involving the CHP system, GSHP system, heat storage, electricity storage, and a biomass boiler.

- Considering the supply-side management of retrofitting energy devices

The optimal operating schedules of each active energy device are obtained in the second-set optimisation to minimise the overall operating energy consumption. The year-round profile of heating demand,

Table 5
The optimal design configuration from the first-set optimisation.

Cases	1	2	3	4	5	6	7
$R_{rec,ES}$	0.9	0.5	0.1	0.5	0.5	0.5	0.5
$R_{rec,CHP}$	0.5	0.5	0.5	0.9	0.5	0.5	0.5
$R_{rec,PV}$	0.5	0.5	0.5	0.5	0.5	0.9	0.1
C_{CHP} (kW)	70	90	95	85	90	60	100
A_{SH} (m^2)	1250	1100	1100	1000	1200	1000	900
A_{PV} (m^2)	14000	31000	30000	32000	32000	35000	27000
V_{HS} (m^3)	1336	1172	1114	1298	1125	1627	1160
C_{ES} (kWh)	148622	31613	31489	31932	32330	35503	40261

electricity demand, solar heating production and solar electricity demand are depended on the weather profile, building characteristics and energy device features. Meanwhile, the optimal charging/discharging rate of heat and electricity storage is determined to effectively move energy demands from the peak periods to valley periods. Moreover, the operating capacity of GSHP and CHP systems at different duration of the year are determined to ensure that they are operated at their high efficiency as much as possible.

- Considering the interaction between heating and electricity supply

The energy balance between demand and supply is considered in the second-set optimisation. The electricity consumption of GSHP is considered as a part of electricity demand, which needs to be satisfied by the accumulated electricity supply through the CHP system, PV panel and power grid. Meanwhile, the CHP system can be adopted to simultaneously supply heat and electricity. Therefore, the interaction between heat and electricity supply is taken into account when balancing the thermal and electrical aspects of the building demand side and integrated energy system supply side.

- Interactive retrofitting plan at both design and operating stage

The **optimal retrofitting plan** and corresponding **optimal operating schedule** are achieved by carrying out two sets of optimisations: the **optimal retrofitting plan** from the first-set optimisation is adopted as operational constraints in the second-set optimisation. Meanwhile, the **optimal operating schedule** from the second-set optimisation is used as part of the objective function in the first-set optimisation. Therefore, the initial design and actual operating capacity of each active energy device can be decided interactively and iteratively to ensure that the design of optimal retrofitting solution can effectively suit its optimal year-round operation.

6.2. Main findings

In this study, the historical energy consumption profile, building thermal properties, historical weather profile, and life-cycle inventory data are adopted to replicate the real-world case. To learn the energy performance of each retrofitting energy devices, four reference retrofitting situations are adopted to gain insights into the effects of changing design capacity on the trade-off between embodied impacts and

Table 6
Life-cycle energy consumption in different cases.

	Recycle ratio			Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
	Electricity storage	CHP system	PV panel							
Life-cycle energy consumption (×10^8 kWh)	0.9	0.5	0.5	0.73	0.86	0.85	0.86	0.87	0.87	0.83
	0.5	0.5	0.5	1.80	1.09	1.11	1.10	1.10	1.13	1.12
	0.1	0.5	0.5	2.87	1.32	1.30	1.32	1.33	1.38	1.41
	0.5	0.9	0.5	1.80	1.08	1.07	1.06	1.09	1.12	1.11
	0.5	0.1	0.5	1.81	1.13	1.13	1.14	1.12	1.13	1.14
	0.5	0.5	0.1	1.62	0.68	0.69	0.67	0.68	0.66	0.77
	0.5	0.5	0.9	1.98	1.49	1.47	1.50	1.52	1.58	1.46

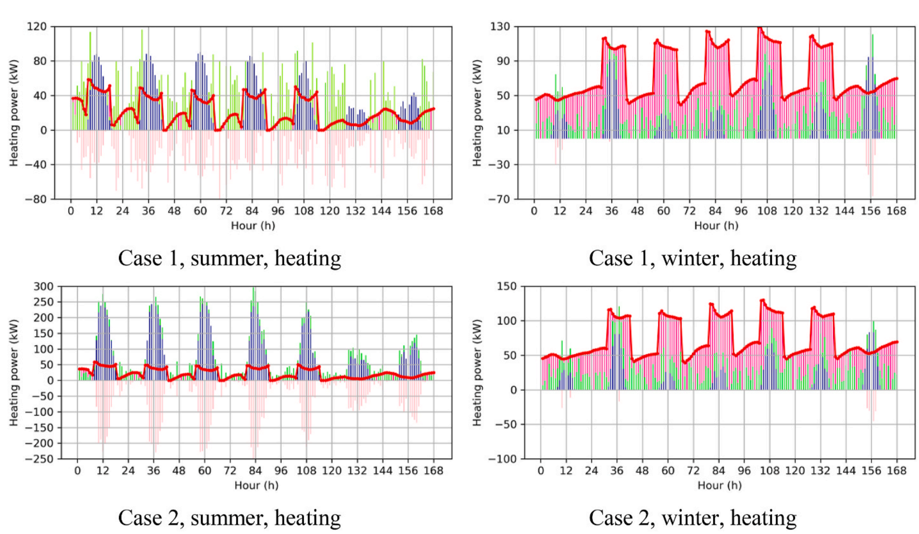


Fig. 23. Optimal operating plan of each retrofitting energy device.

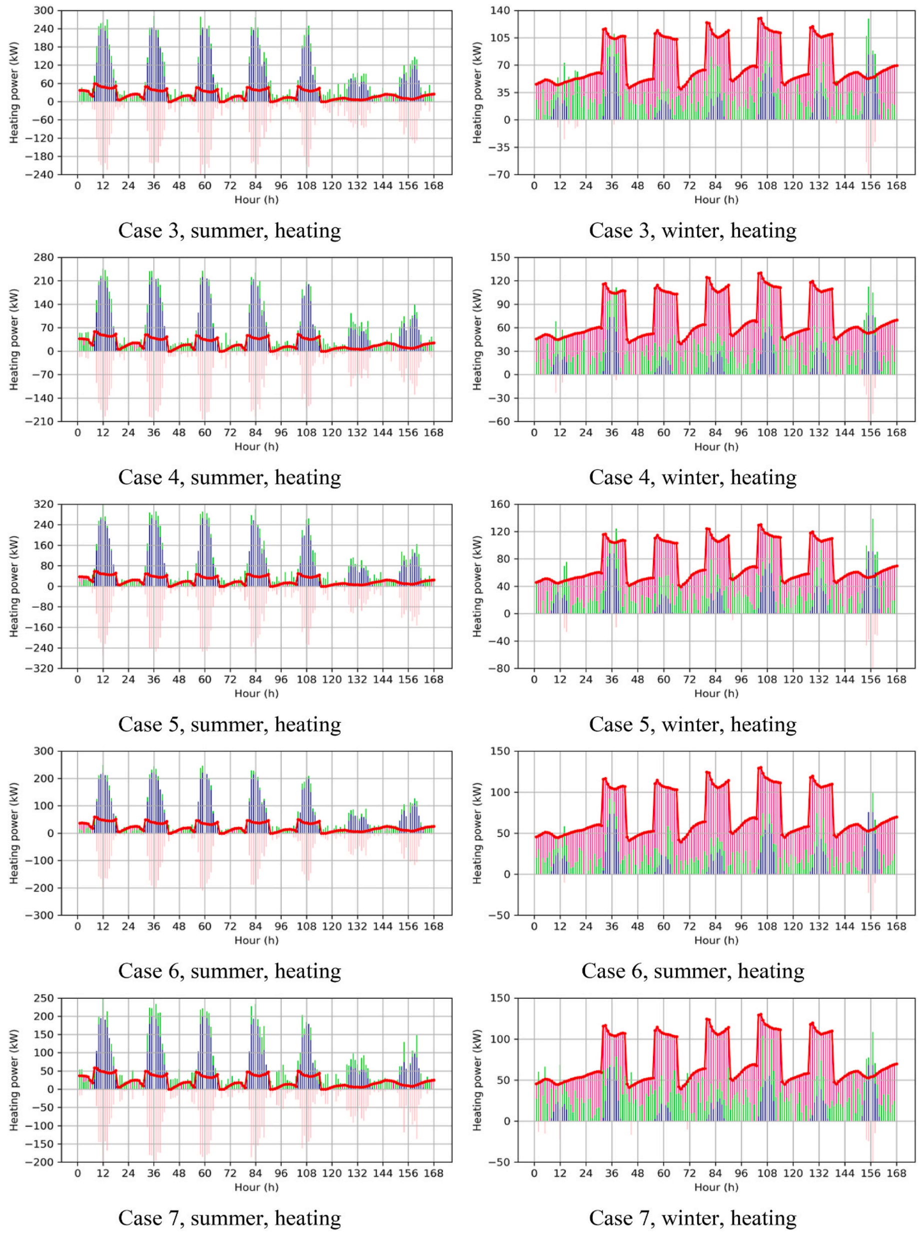


Fig. 23. (*continued*).

operating impacts. The effects of the end-life recycle ratio of retrofitting energy devices are also investigated. The main conclusions are summarised as follow:

- In Situation 1, solar thermal collector and heat storage are collectively used to provide thermal energy. With the design area of the solar thermal collector increases from 1500 m^2 to 6000 m^2, the design capacity of heat storage decreases from 1745 m^3 to 447 m^3. When $R_{HS} = 0.1$ and $R_{SH} = 0.5$ or 0.9, or when $R_{HS} = 0.5$ and $R_{SH} = 0.9$, the life-cycle energy consumption decreases with the increasing design area of solar thermal collector. Moreover, when $R_{HS} = 0.9$ and $R_{SH} = 0.1$ or 0.5, or when $R_{HS} = 0.5$ and $R_{SH} = 0.1$, the life-cycle energy consumption increases with the increasing design area of solar thermal collector. When the end-of-life recycle ratio of heat storage and solar heat is equal, the minimum embodied energy is identified when the area of the solar thermal collector is 2500 m^2.
- In Situation 2, PV panel and electricity storage are collectively used to provide electrical energy. With the PV panel area increasing from 12800 m^2 to 50000 m^2, the capacity of electricity storage decreases from 2.22×105 kWh to 8604 kWh. Due to the high embodied energy of electricity storage, its capacity has a substantial effect on life-cycle energy. With the increasing area of PV panels, the life-cycle energy decreases. When the recycle ratio of electricity storage is higher than that of PV, the life-cycle energy will increase when the design area of the PV panel is larger than 35,000 m^2. When the end-of-life recycle ratio of electricity storage and PV panel is equal, the total embodied energy would decrease with the increasing design area of PV panel.
- In Situation 3, the solar thermal collector, heat storage and biomass boiler are collectively used to provide heating energy. The design capacity of heat storage decreases with the increasing design capacity of biomass boiler and increasing design area of PV panel. The immense contribution is from the embodied energy of heat storage, followed by the embodied energy of solar thermal collector as well as embodied energy and primary energy consumption from the biomass boiler. When the recycle ratio of heat storage is 0.1, the life-cycle energy consumption is almost consistent at different rated capacities of the biomass boiler. When the recycle ratio of heat storage is

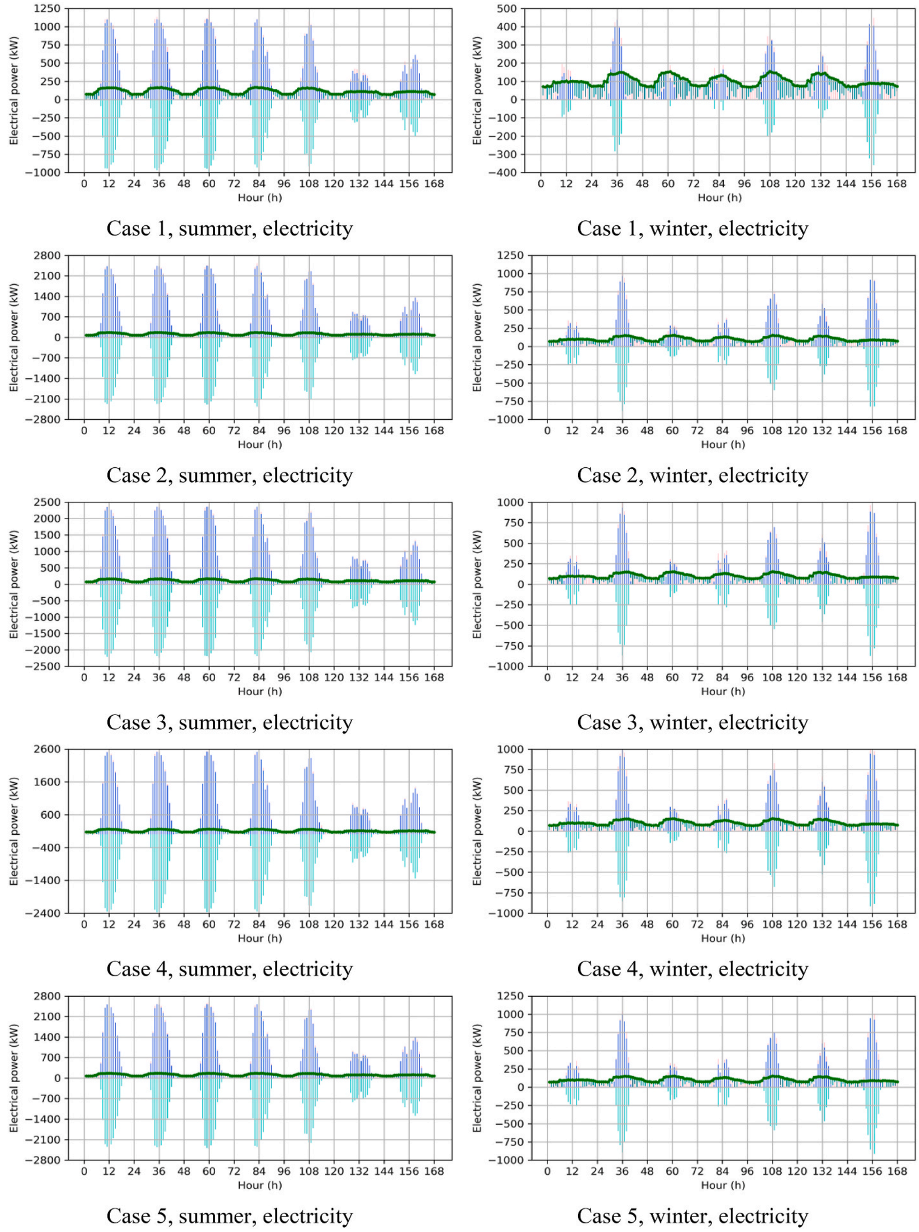


Fig. 23. (*continued*).

0.5 or 0.9, the life-cycle energy consumption slightly rises with the rise of the design capacity of the biomass boiler. Moreover, the equivalent annual life-cycle energy consumption decreases with the increase of life span.

- In Situation 4, PV panel and electricity storage are collectively used to provide electrical energy, while the power grid can also export electricity to the building when necessary. With the increased design area of PV panels, the embodied energy of PV panels increases, while the embodied energy of electricity storage and operating primary energy consumption decreases. When the recycle ratio of electricity storage is 0.1 or 0.5, the life-cycle energy consumption decreases with the increase of PV panel area, while the lowest life-cycle energy consumption is identified when the PV panel area is around 40,000–60,000 m^2. When the recycle ratio of electricity storage is 0.9, the life-cycle energy consumption will rise with the rise of the PV panel area. When the limited electricity importation rate is smaller than 50 kW, the smallest life-cycle energy consumption is identified when the design area of the PV panel is 50,000 m^2.

More importantly, the proposed interactive retrofitting optimisation approach is adopted in two different situations. In the first situation, the retrofitting options include heat storage, electricity storage, PV panel, solar thermal collector and GSHP system. In the second situation, the retrofitting options include heat storage, electricity storage, PV panel, solar thermal collector and CHP system.

The first-set optimisation and second-set optimisation is conducted to iteratively decide the optimal design configuration and operating plan, respectively.

- The optimal design configuration of both passive retrofitting options (i.e. PV panel and solar thermal collector) and active retrofitting options (i.e., CHP system or GSHP, electricity storage and heat storage) can be obtained from the first-set optimisation. It is also seen that the different end-life recycle ratios would result in different design capacities of each retrofitting device.
- Meanwhile, the optimal operating plan can be obtained from the second-set optimisation. The operating plan is optimised to satisfy effective supply-side management of different energy devices. The

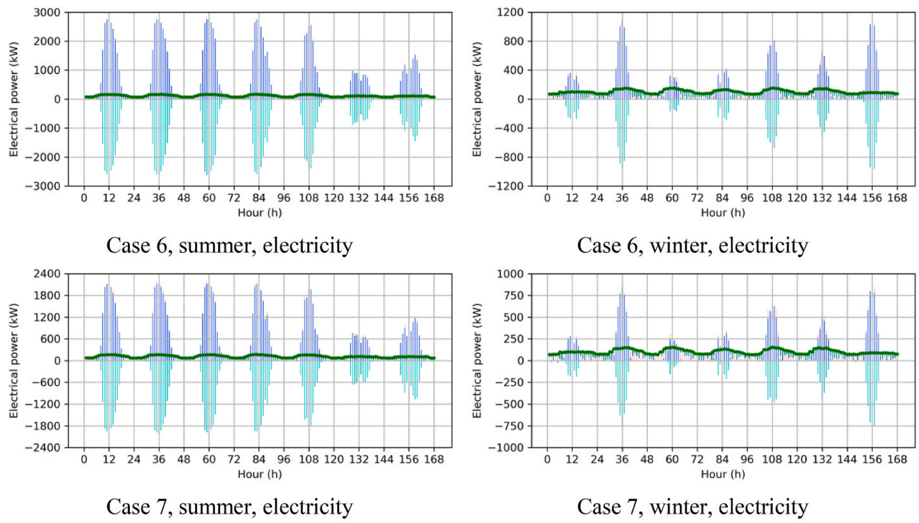


Fig. 23. (*continued*).

interaction between heat and electrical energy through GSHP and CHP systems is also considered. During the daytime, the electricity is mainly provided by the PV panel when solar radiation is sufficient, while the excess electricity generated by the PV panel is used to charge the electricity storage. If the electricity production from PV panels is not sufficient to satisfy electricity demand, the CHP system and electricity storage will work cooperatively to satisfy electricity demand. In summer, the heating demand is small, while thermal energy production from the solar thermal collector is high; thus, the excess heating energy generated by the solar thermal collector is adopted to charge the heat storage. During other periods, if the thermal production from the solar thermal collector is not sufficient to satisfy the heating demand, the CHP system or GSHP system and heat storage would work cooperatively to meet building heating demand.

6.3. Future works

There are several future research directions to further improve the life-cycle performance of building retrofitting measures.

- In the current study, the retrofitting optimisation approach is implemented in an office building. The retrofitting performance of other types of buildings (e.g., residential, commercial, hospital, hotel, etc) under different climate conditions should also be investigated.
- In the current study, the retrofitting options mainly focus on market-available materials (i.e., PV panel, solar thermal collector, wind turbine, CHP system and GSHP system). The performance of building integrated photovoltaic/thermal systems [54] and building integrated bifacial photovoltaic façades [55,56] in building retrofitting should be investigated, especially those with the latest technologies, such as biopolymer electrolytes-based solar cells [57], Aqueous dye-sensitised solar cells [58] and solid-state electrolyte-based solar cells [59]. Meanwhile, the performance of photo-electrochromic systems-based smart windows [60] in building retrofitting can also be considered.
- In the current study, only supply-side management is considered. It is worthwhile to integrate life-cycle optimisation, supply-side management and demand-side management together to achieve better energy-saving performance in retrofitting towards smart and sustainable building [61]. Moreover, it is important to understand the impacts of the built environment on occupant cognitive function and mental health [62].

Credit author statement

Xiaojun Luo: Conceptualization, Methodology, Software, Validation, Writing – original draft, Writing – review & editing, Resources, Data curation, Visualization. Lukumon Oladayo Oyedele: Supervision, Funding acquisition, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

A	Design area
C	Design capacity
COP	Coefficient of Performance
D	Energy demand
e	Unit energy
E	Energy
G	Solar irridiance
N	Number
PLR	Part load ratio
Q	Operating capacity
r	Charging/Discharging rate
R	Recycle ratio
α	Coefficient of solar thermal collector
ρ	Pheromone
η	Efficiency
ε	Correction coefficient of PV panel

Subscripts

BB	Biomass boiler
CHP	Combined heat and power system
ch	Charge

dch	Discharge
e	Electrical
eq	Electrical equipment
ext	External
EMB	Embodied
ES	Electricity storage
G	Grid
GSHP	Ground source heat pump system
h	Heating
HS	Heat storage
inf	Infiltration
int	Internal
l	Lighting
LC	Life cycle
LS	Life span
n	Nominal
o	Occupancy
OP	Operating
PV	Photovoltaic panel
ref	Reference
REC	Recycled
SH	Solar thermal collector
trans	Transmission
vent	Ventilation

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